SMPTE Meeting Presentation

Gamut Mapping for Digital Cinema

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Abstract. *To ensure consistent presentation of wide gamut Digital Cinema Packages (DCPs) on standard gamut screens, a mandatory gamut mapping strategy has to be chosen. In this paper, current gamut mapping algorithms are evaluated with respect to their application in digital cinema. These algorithms include: "Simple Clip", "Cusp Clip", "Minimum delta E" (MindE), "Hue preserving MindE", "Weighted MindE" and the mapping strategy which is used in current projectors. The investigated gamut mapping algorithms will be provided as 3D lookup tables for comparison. These can also be used to retrofit a more advanced gamut mapping strategy to standard gamut projectors. Therefore, the paper closes with an analysis of the losses introduced by using 3D lookup tables for gamut mapping. The intent of this paper is to initiate a discussion about gamut mapping strategies for digital cinema, which may ultimately lead to an addendum to the SMPTE standards for digital cinema.*

Keywords. gamut mapping; digital cinema; digital projection

Introduction

The rollout of digital cinema is a story of success. Nowadays digital cinemas offer a more precise colorimetry than 35mm projection could offer. This success is based on the decisions of the Digital Cinema Initiatives (DCI) and SMPTE DC-28 to employ non-mainstream image coding technologies like the DCI-X'Y'Z' color space[1].

One of the primary goals of the DCI specification is to build a specification that is not tied to particular mastering- or projection technologies. This is achieved by encoding digital cinema packages (DCPs) in DCI-X'Y'Z' color space, which is independent of today's projection primaries. Figure 1 illustrates the range of colors that can be encoded within the DCI-X'Y'Z' color space (1.1). They surpass the range of colors, visible to the human eye, which is indicated by the horseshoe shaped lines. The volume of colors a projector can display is called the projector's gamut. To guarantee a minimum number of colors that can be reproduced on any digital projection system, the P3 reference gamut (P3ref) (1.2) is defined in SMPTE 431-2[2]. A P3ref projector can only display a subset of the colors encoded in DCI-X'Y'Z', while a prototype laser projector[3] (P3laser) (1.3) covers extended colors compared to P3ref but is still not able to show all valid DCI-X'Y'Z' colors.

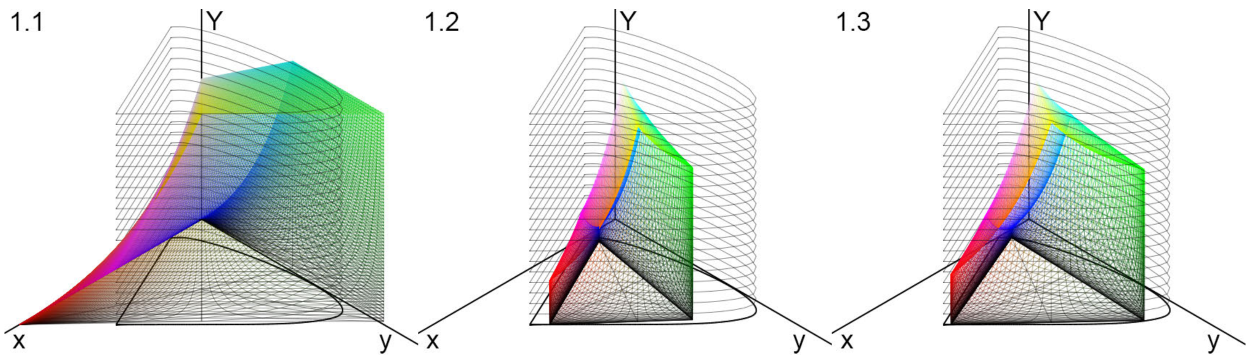

Figure 1. DCI X'Y'Z' color space (1.1) compared to DCI reference projector gamut "P3ref" (1.2) and the gamut of a prototype laser projector "P3laser" (1.3) from the OSIRIS project[3]. The lower axes x and y are the CIE 1931 chromaticity diagram x- and y-axes, the vertical axis is the Y-component of the CIE 1931 2° standard observer.

Colors, which are outside the gamut boundary and therefor can't be reproduced are called out-of-gamut colors. To be displayed, they need to be mapped to in-gamut colors. This is done by gamut mapping algorithms. These describe the way a particular display maps out-of-gamut colors to in-gamut colors. Gamut mapping can be done in multiple ways. This makes it possible to transfer the same out-of-gamut color to different in-gamut colors. The obtained in-gamut color does not only depend on the gamut mapping algorithm used, but also on the color space in which the mapping is performed.

Current digital cinema standards (SMPTE ST 428 to 431) do not define a mandatory gamut mapping strategy for digital cinema projection. As the results of gamut mapping cannot be foreseen for all digital cinema projectors, a lot of postproduction companies limit the gamut of distribution DCPs to P3ref by using their own gamut mapping strategy. This procedure prevents unexpected results in projection for colors outside of the P3ref gamut. Performing gamut mapping during mastering did not introduce any noticeable issues until the introduction of laser projectors. But when DCPs will be mastered to benefit from the wider gamut of laser projection, it will be inevitable that legacy projectors perform gamut mapping to their native color space. This process should be standardized to ensure a consistent image presentation on all deployed projectors.

The goal of our work is to assist this standardization work by giving an overview of gamut mapping algorithms and mapping spaces that are suitable for digital projection scenarios. We provide an analysis on the characteristics of gamut mapping algorithms and color appearance models used for gamut mapping in respect to the application for digital cinema. In addition, we supply 3D lookup tables (LUTs) to enable the industry to evaluate the different mapping strategies with their individual test images. Finally we inspect how to retrofit legacy projectors to support new gamut mapping strategies.

Methods

Gamut mapping for digital cinema according to the SMPTE digital cinema standards provides clearly defined requirements and conditions. In contrast to gamut mapping from cinematic environment to television presentation, in cinema to cinema gamut mapping, tone mapping is not needed as the defined white stays at $48cd/m^2$ and the lightness compression in the blacks, that is needed to adapt to different contrast ratios, is already handled by the relative lightness coding[4]. The viewing conditions, that are relevant when converting to a color appearance model for performing gamut mapping, also stay the same between different projectors, since all cinemas feature a comparable dark surrounding.

Color Spaces for Gamut Mapping

If the goals of gamut mapping are specified in terms of appearance attributes like lightness, chroma and hue, the image has first to be transferred to a color space that is as perceptually linear in these attributes, and as uniform as possible[5]. E.g. if no alteration of hue is desired, there must be a possibility to separate hue from the other appearance attributes.

The most widely used color space that tries to achieve perceptual uniformity is CIE L*a*b* 1976[6] It serves as basic reference color space for gamut mapping[7]. In print applications, gamut mapping is commonly done in CIECAM02 color space[8,5]. Unfortunately, CIECAM02 is ill defined for saturated colors near the spectral locus, when used with cooler whitepoints than D50[9]. Therefore a modified CIECAM02 formula according to Li[10] (CIECAM02-HPE) is employed using Hunt-Pointer-Estevez LMS cone space for adaption, instead of the sharpened CAT02. Another color space intended for gamut mapping is LAB2000HL[11]. We did not consider LAB2000HL in our survey as the reference implementation also failed to encode colors near the spectral locus. Fritz Ebner's IPT[12] completes the selection of color appearance models included in our survey.

All three color appearance models need a mastering white point as parameter to emulate chromatic adaption. Because DCPs can be mastered with different white points, but the white point is generally not included in the DCP metadata, D60 white point was assumed for all conversion processes.

Selected Gamut Mapping Algorithms

Since DCI-X'Y'Z' colorimetry encodes absolute projected colors, no alteration of in-gamut colors is desired. Color compression inside the gamut boundary would break backward compatibility, as it would change the color reproduction of existent DCPs on deployed projectors. We therefore chose to only include gamut-clipping algorithms into our survey. But it should be noted that gamut mapping algorithms applying gamut compression manage to preserve more spatial details in saturated image areas. Thus, gamut compression algorithms should be reconsidered in case of a major redesign of the digital cinema color encoding system.

To identify the gamut mapping algorithm used by current projectors we analyzed the handling of in-gamut and out-of-gamut colors supplied to a Barco DP90 projector, which was set up to receive a DCI-X'Y'Z' coded signal at the input. The projected colors were measured using a spectroradiometer. Figure 2 shows the submitted colors (red points) and the measured values (green points) with respect to the projector red and green primary colors as basis. In this representation, the gamut mapping algorithm of the projector becomes apparent. It seems to first convert X'Y'Z' values to it's native color space and then simply clip these values each to the range between off (0) and full intensity (1) of the particular primary color. Note that mapping X'Y'Z'-values to a color space that is spanned by the primary colors of the projector leads to values below 0 and above 1. These values represent physically impossible "negative light" and more intensity from the respective primary color than the projector is able to supply. Thus the values below 0 and above 1 can't be displayed with this set of primary colors. In the following we assume all DLP-Cinema™ projectors perform gamut mapping by clipping into their native color space and call this gamut mapping algorithm PCLIP for "Post-CLIP".

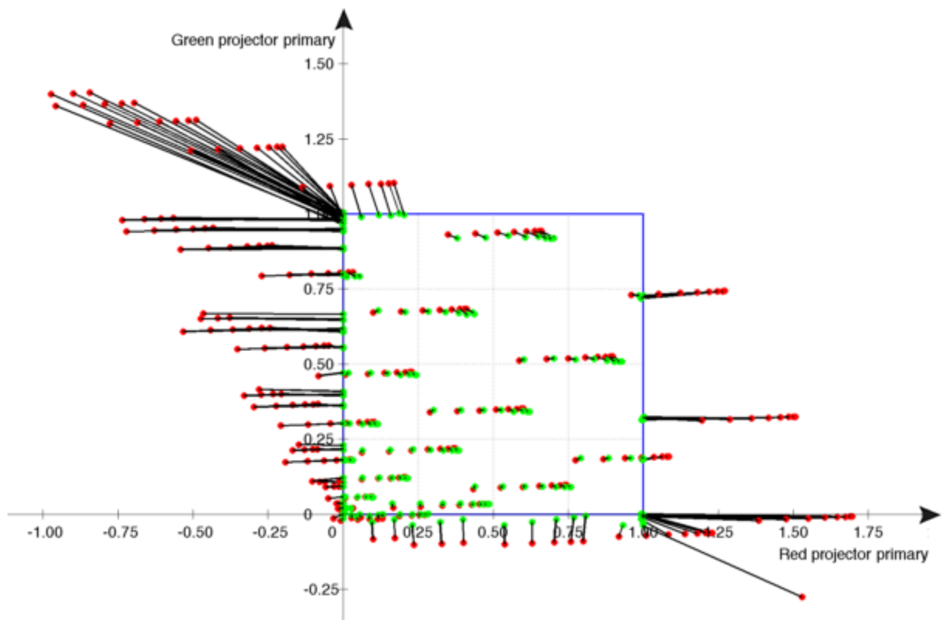

Figure 2. Visualization of the gamut mapping algorithm of a Barco DP90 projector. The x-axis describes the amount of the projectors native red primary color needed to show a particular color. The y-axis shows the same for the projector's green primary. Red dots represent the source colors consisting of all combinations of DCI X'Y'Z' values {0, 512, 1024, 1536, 2048, 2559, 3071, 3583, 4095} that represent real colors. The green dots are the colors measured on screen. To highlight the gamut mapping strategy, all source colors are connected to the resulting colors with a black line.

As PCLIP's truncation of individual color channels results in hue shifts and loss of detail, additional gamut mapping algorithms are investigated. The way they map out-of-gamut colors onto the gamut boundary is illustrated in Figure 3. When available, the notation is inherited from Jan Morovic's book on color gamut mapping[5]:

3.1 PCLIP (Post clip) is the gamut mapping algorithm measured from a DLP-Cinema™ projectors. It clips values that the projector can't display in the color space that is spanned by its primary colors.

3.2 LCLIP[13] preserves hue and lightness of out-of-gamut colors but reduces chroma until the gamut boundary is reached.

3.3 SCLIP[13] projects out-of-gamut colors onto the gamut surface, in the direction of one point. Mid gray is a common value for this target point.

3.4 CCLIP[14] (Cusp clip) projects all out-of-gamut colors towards points on the gray-axis. The lightness of the respective point is determined by the lightness of the target gamut cusp at the hue-angle of the particular out-of-gamut color. E.g. yellowish colors are projected towards a lighter gray than bluish colors.

3.5 MindE[13] (minimum delta E) selects the in-gamut color with the minimum colorimetric distance for each out-of-gamut color. For the color appearance models used here, colorimetric distance is equivalent to the geometric distance of two points in L, a, and b coordinates.

3.6 HPmindE[15] (Hue preserving mindE) works like standard MindE but restricts the search for the nearest in-gamut color to colors with the same hue.

3.7 WmindE[16] (Weighted mindE) also belongs to the family of minimum distance algorithms, but uses different weights for Lightness, Chroma and Hue. The parameters used in this paper are 1, 2.6, and 1.3 for lightness, chroma and hue as proposed by Morovic et al. in 2007[17].

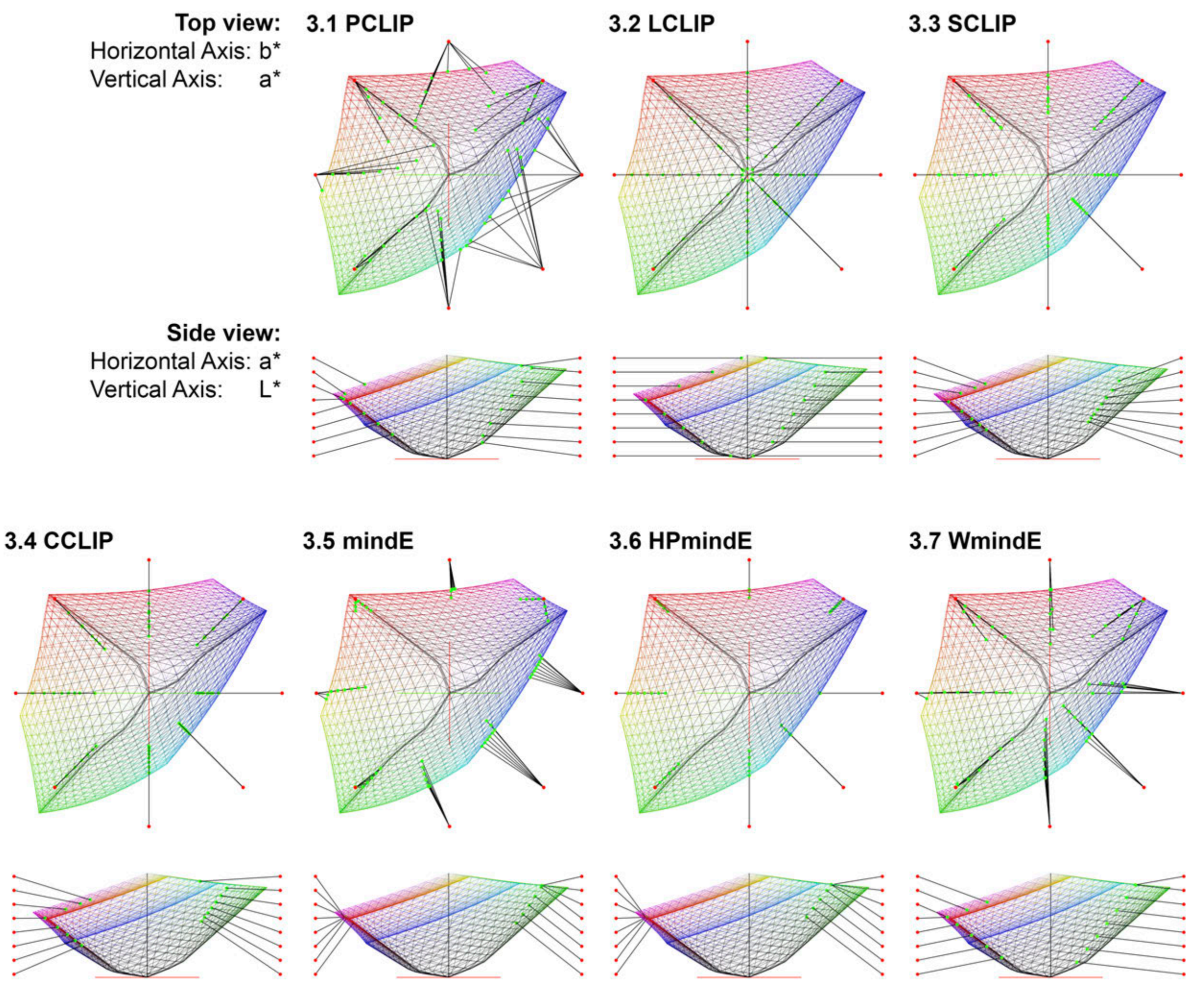

Figure 3. Visualization of the selected gamut mapping algorithms in CIE 1976 L*a*b* color space. The colored grid shows the gamut boundary of P3ref color space. In top view any combination of the L* values { 3, 16, 30, 43, 57, 70, 84, 97} with a*|b* values of {0|0, 91|91, 0|128, -91|91, -128|0, -90|-90, 0|-128, 90|-90} are mapped to in-gamut colors using the respective gamut mapping algorithm. In the side view row the L* values are combined with a*|b* values of {128|0, -128|0 }. These L*a*b* values don't represent real colors but serve to illustrate the different ways the gamut mapping algorithms map colors to P3ref color space.

Results

The presented gamut mapping algorithms were evaluated with the CIE 156[6] images and custom color graded versions of the Kodim[18] images and MATLAB's built-in pepper image. To be able to see the reference images in wide gamut, a DLP-Cinema™ projector was modified with a special notch filter to feature a gamut that is almost as large as the gamut of prototype laser projectors. The wide gamut reference image was presented together with two representations of this image, each gamut mapped to P3ref with a different gamut mapping algorithm for comparison.

Color Spaces for gamut mapping

The mapping spaces L*a*b*, CIECAM02-HPE and IPT all have major drawbacks when used to predict color appearance in cinematic environments. L*a*b* is not hue-linear enough and thus introduces hue-changes when reducing saturation. To illustrate this, Figure 4.1 shows a perceptually linear desaturation of sRGB's primary blue color as predicted by L*a*b*, CIECAM02-HPE and IPT. When reducing saturation in L*a*b* the medium saturated part of the gradient turns towards purple compared to the most saturated tip. This unwanted effect can be observed in gamut mapping where hue linear desaturation often takes place. CIECAM02-HPE and IPT perform much better in terms of hue linearity but due to the convex shape of primary based color spaces in the blue area, minimum distance based algorithms are prone to introducing artifacts when used with these newer models. The mapping of similar out-of-gamut blues to very different in-gamut colors using mindE can be observed in Figure 4.2. In contrast to CIECAM02-HPE, IPT has proven to be more robust, using our test image set. Figure 4.3 shows the same mindE mapping performed in IPT.

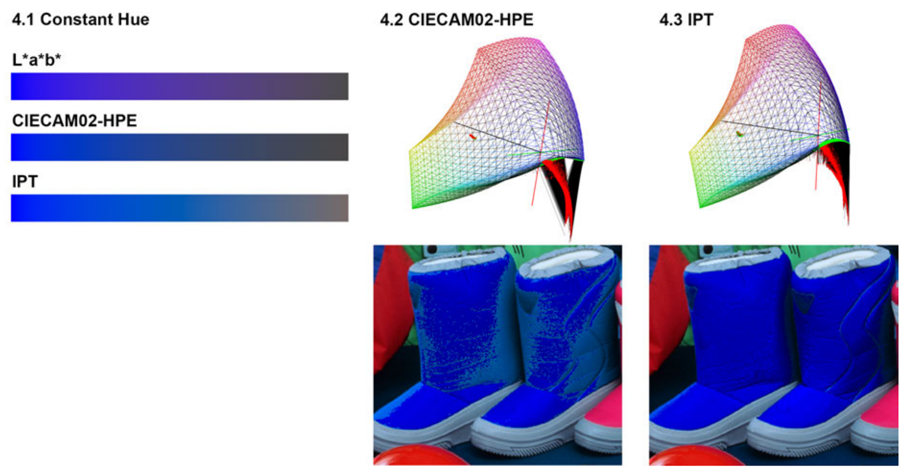

Figure 4. Artifacts introduced by the color space in which the gamut mapping is performed. 4.1 shows bluish colors of different lightness, constant hue and increasing saturation predicted by L*a*b*, CIECAM02-HPE and IPT. In Figure 4.2 a detail from the ISO 165 "Ski" test image[6] is presented along the corresponding 3D-rendering of gamut mapping this image via mindE to sRGB[19] color space.

Gamut mapping algorithms

When evaluating gamut mapping algorithms, results can vary a lot depending on the test images[7]. To illustrate the typical characteristics of the selected gamut mapping algorithms, Figure 5 shows MATLAB's pepper image interpreted with laser projection primaries instead of sRGB primaries and then gamut mapped back to sRGB color space. Please note that mapping from P3Laser to sRGB instead of P3ref exaggerates the characteristics of the individual gamut mapping algorithms. Unfortunately no reference image can be shown in this document as the gamut mapped images already use the maximum available gamut of common monitors.

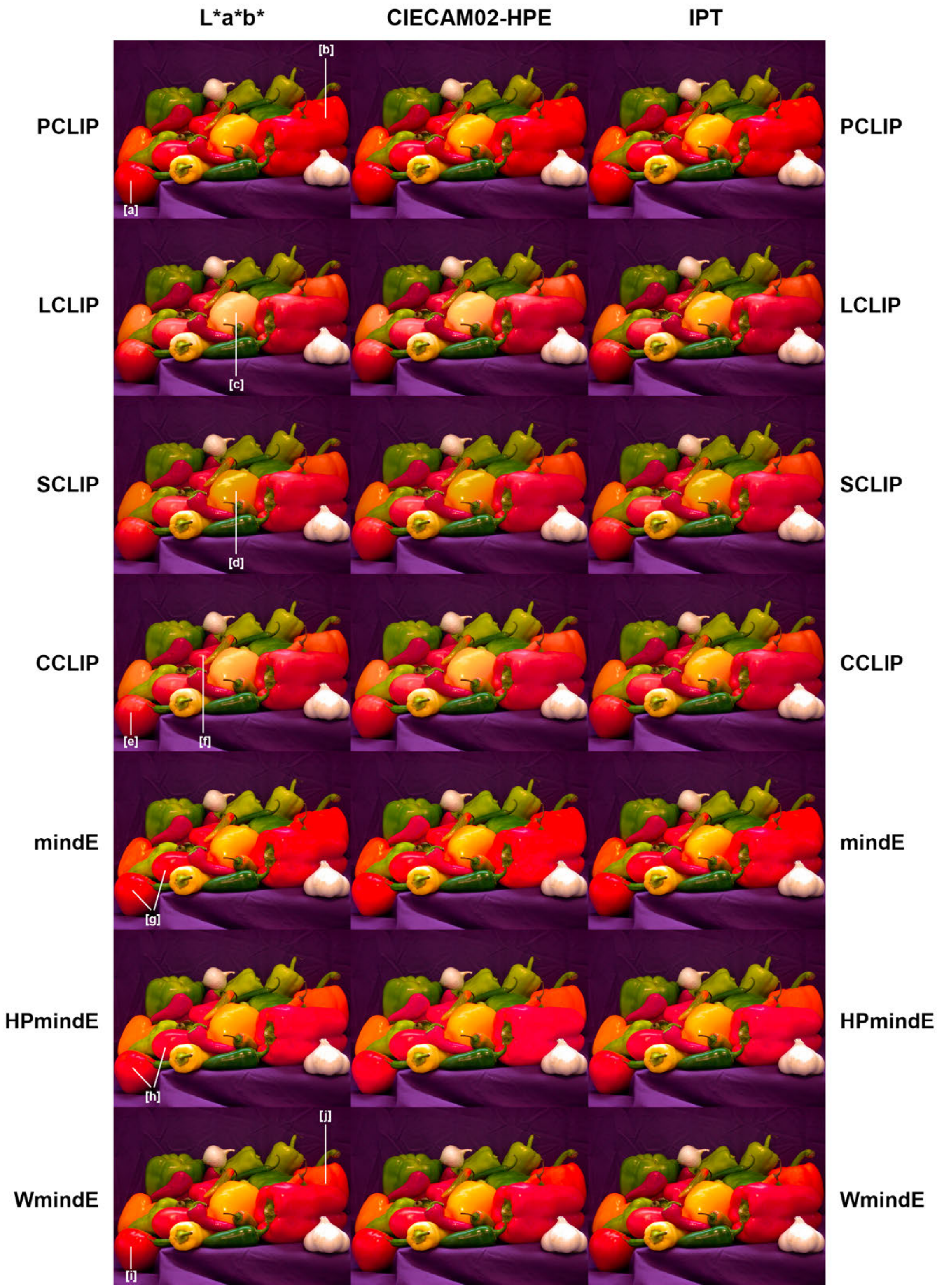

Figure 5. Gamut mapping examples. To be able to be presented on standard monitors, the image was mapped from P3laser to sRGB. Compared to mapping from P3laser to P3ref, this larger step exaggerates the characteristics of the individual gamut mapping algorithms. Please note that due to the additional gamut mapping happening in printing, Figure 5 should only be viewed on sRGB displays. To evaluate the mapping from P3Laser to P3min download the 3D-LUTs from the project website. The peppers image is Copyright The MathWorks, Inc. and is used with permission.

When looking at the first row of Figure 5 it can be observed that PCLIP retains saturation but reduces details, e.g. most of the specular highlight in the left tomato[a] is lost. Also, if only a single color channel is clipped, hue changes occur. This can be seen in the rear orange pepper on the right[b]. All three PCLIP images are identical because PCLIP uses the target color space as gamut mapping space instead of a color appearance model. In contrast to PCLIP, the LCLIP algorithm preserves hue and lightness but chroma can change drastically. This appears in saturated out-of-gamut colors like the yellow pepper in the middle[c], mainly in the L*a*b* and IPT columns. This yellow color could be transferred to in-gamut with a minimal change in lightness but it is instead desaturated a lot by mapping towards white. While LCLIP renders bright saturated colors even brighter, the SCLIP algorithm results in the darkening of bright colors. Again note the yellow pepper in the middle[d]. As a compromise CCLIP prevents the darkened highlights of SCLIP but like SCLIP and LCLIP preserves details at the cost of lost saturation. The tomato on the left[e] and the red pepper hidden behind the yellow pepper in the middle of the image[f], serve as good examples.

While approaches seeking the minimum distance like the mindE algorithm seem to be the best solution if the mapping space is perceptually linear, they introduces severe problems. If the gamut boundary of the target gamut is concave, out-of-gamut colors that are very close to each other may be projected to much more distant in-gamut colors, as illustrated in Figure 4.2. Lost details[g],[h] near the peaks of the digital projection gamut are another disadvantage that all algorithms searching for minimum distance suffer from. This is less an issue in print applications, where the target gamuts are generally rounder than the pointed digital projection gamuts. MindE and HPmindE are particularly affected from this problem. For an illustration of this problem see the projection of the different synthetic red tones to one color in Figure 3.5. In contrast to mindE and HPmindE, WmindE preserves more details but still retains a lot of saturation. Again see the tomato on the left[i] and the two peppers on the right[j].

In summary, using the test images described above, it can be observed that WmindE performs best for digital projection. It offers a compromise between the preservation of saturation of the PCLIP algorithm and the retained hue and details from L-, S-, and CCLIP gamut mapping algorithms.

Implementing gamut mapping by means of 3D lookup tables

In the following section we analyze the artifacts introduced by using 3D LUTs for implementing gamut mapping into existing digital cinema projectors. 3D LUTs can be inserted in the processing path of DLP-Cinema™ projectors[20]. Series 1 projectors offer a 3D LUT precision of up to 49x49x49 lattice points but series 2 projectors are limited to a precision of 17x17x17[21]. The top row of Figure 6 shows a gradient test image that is gamut mapped from P3laser to P3ref using WmindE. In comparison, the same gradient is shown gamut mapped via a 3D LUT in the second row. Note the waves in the upper red part of the gradient in the image mapped by the 17x17x17 3D LUT. In the bottom row, the differences between the two images are shown in CIE1976 delta E. As can be seen in the second column, increasing the 3D LUT precision to 49 steps helps but does not prevent small, just noticeable differences in synthetic images, especially at the boundary of the P3ref gamut.

As a conclusion, the 3D LUT size found in DLP-Cinema™ Series 2 projectors is not sufficient to support visually lossless gamut mapping. Only series 1 projectors can be retrofitted to support advanced gamut mapping via a simple X'Y'Z' to X'Y'Z' 3D LUT. In our real-world test images, no differences were perceived between direct gamut mapping and gamut mapping via a 49 step 3D LUT. By using methods for improving 3D LUT precision for gamut mapping[22] the performance of this 3D-LUT might be further enhanced.

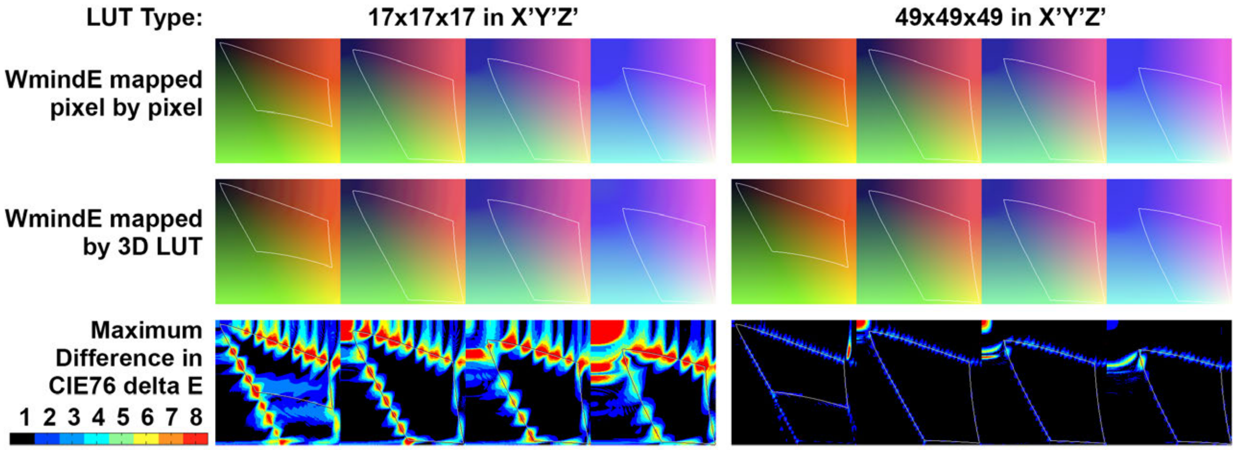

Figure 6. Four gradients in P3laser color space, each gamut mapped to P3ref. The first row is mapped directly, the second row via 3D LUT and the third row illustrates the differences between the correct mapping and the implementation by 3D LUT. The P3ref gamut boundary is indicated by a white line. In the first two rows, the gradients are converted back to P3laser color space and are then interpreted as sRGB to be able to be shown in this paper.

Conclusion

With the introduction of laser projectors, DCPs will be mastered for wider gamuts. As different gamut mapping algorithms generate divergent results, gamut mapping for digital cinema needs to be standardized to ensure a predictable presentation on all screens.

The PCLIP algorithm, presumably used in current projectors, tends to result in hue-shifts and loss of detail. But it can easily be implemented without using a 3D LUT. Among the evaluated gamut mapping algorithms, WmindE in IPT is a promising candidate. It can preserve more details and hue than PCLIP without introducing artifacts in the evaluated image set.

DLP Cinema™ Series 1 projectors can currently be retrofitted with a new gamut mapping algorithm using a 3D LUT. Series 2 projectors would need hardware modifications to support 3D LUT processing with a sufficient precision.

We invite the industry to evaluate the presented gamut mapping algorithms with a large variety of images. To facilitate this, all gamut mapping algorithms presented in this paper are available for download as 3D-LUTs at http://www.hdm-stuttgart.de/~froehlichj. When consensus is reached which algorithm performs best, this gamut mapping strategy should be added to the digital cinema projection standards.

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Gamut Mapping for Digital Cinema

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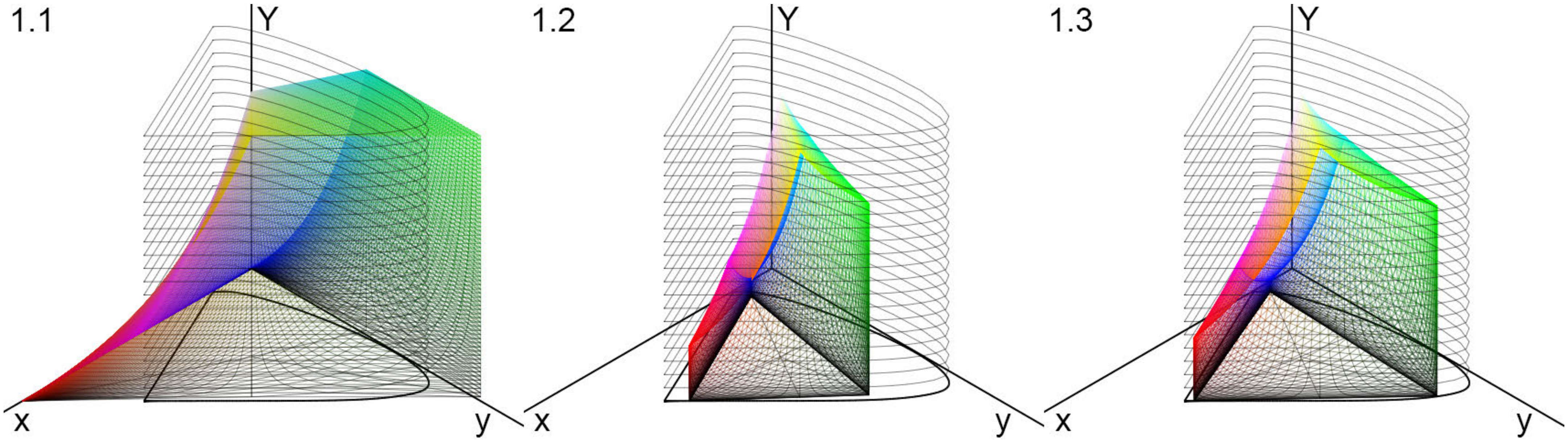
Motivation

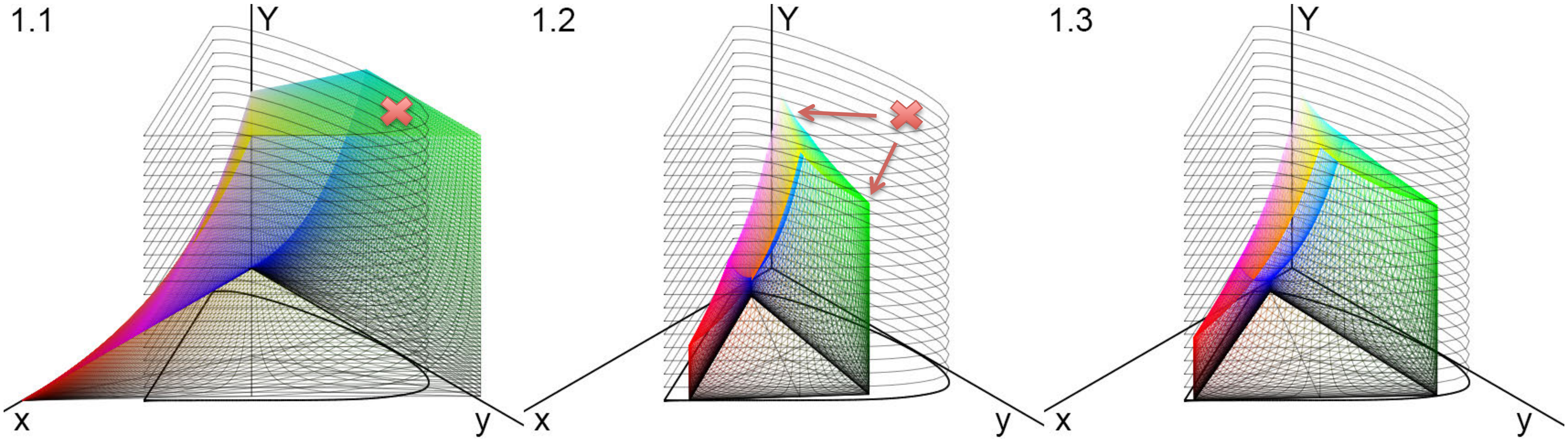
- DCPs are encoded in DCI X'Y'Z'



- DCI X'Y'Z' (1.1): Device independent image coding
- P3ref (1.2): Minimum gamut defined
- P3laser(1.3): Extended Gamut of Laser projectors

Motivation

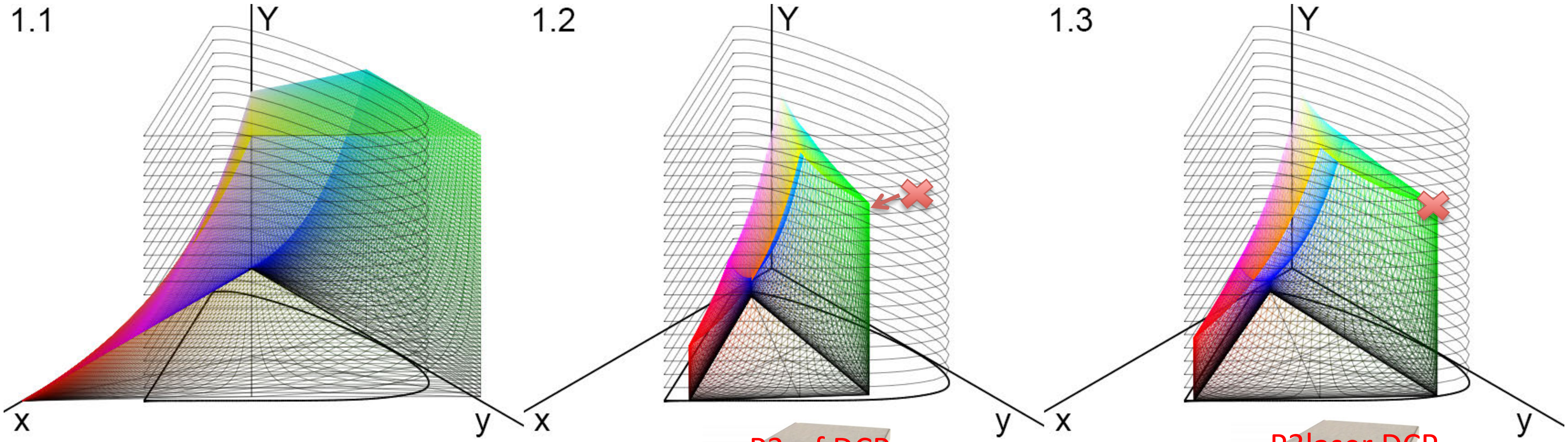
- DCI X’Y’Z’ encodes much more colors than can be displayed:



- Gamut mapping must be performed by the display device for out-of-gamut colors.
- This can be done in several ways

Motivation

- DCI X'Y'Z' encodes much more colors than can be displayed:



- Master 2 DCPs?

- Better define one mandatory gamut mapping algorithm for all projectors and stay device independent

Outline of the talk

- Why is gamut mapping for digital cinema relevant today?

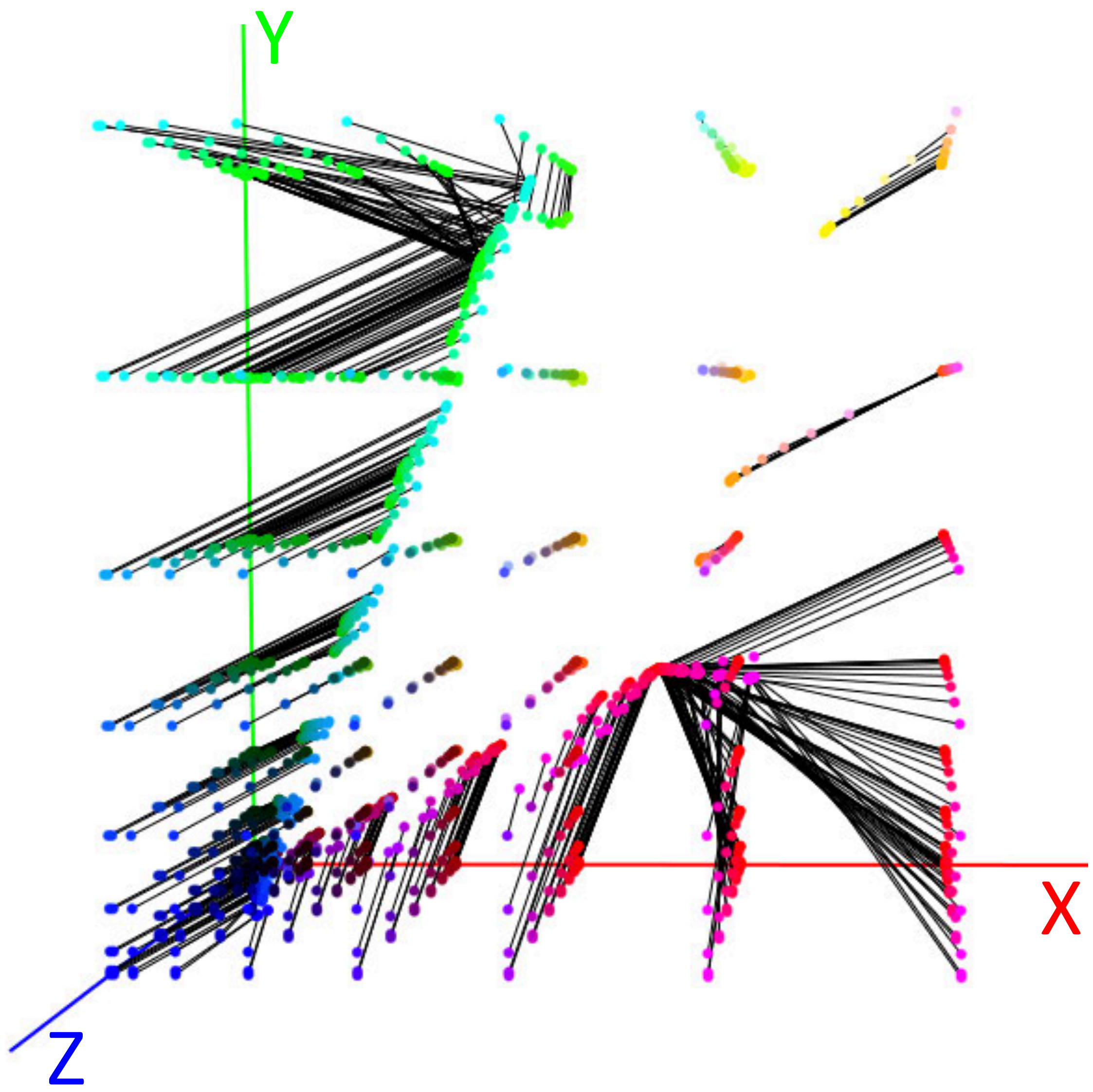
- Overview of gamut mapping algorithms and mapping spaces.
- Evaluation of gamut mapping algorithms.
- Implementation.

- Call to action!

Current projector's gamut mapping

How do current projectors handle out-of-gamut colors?

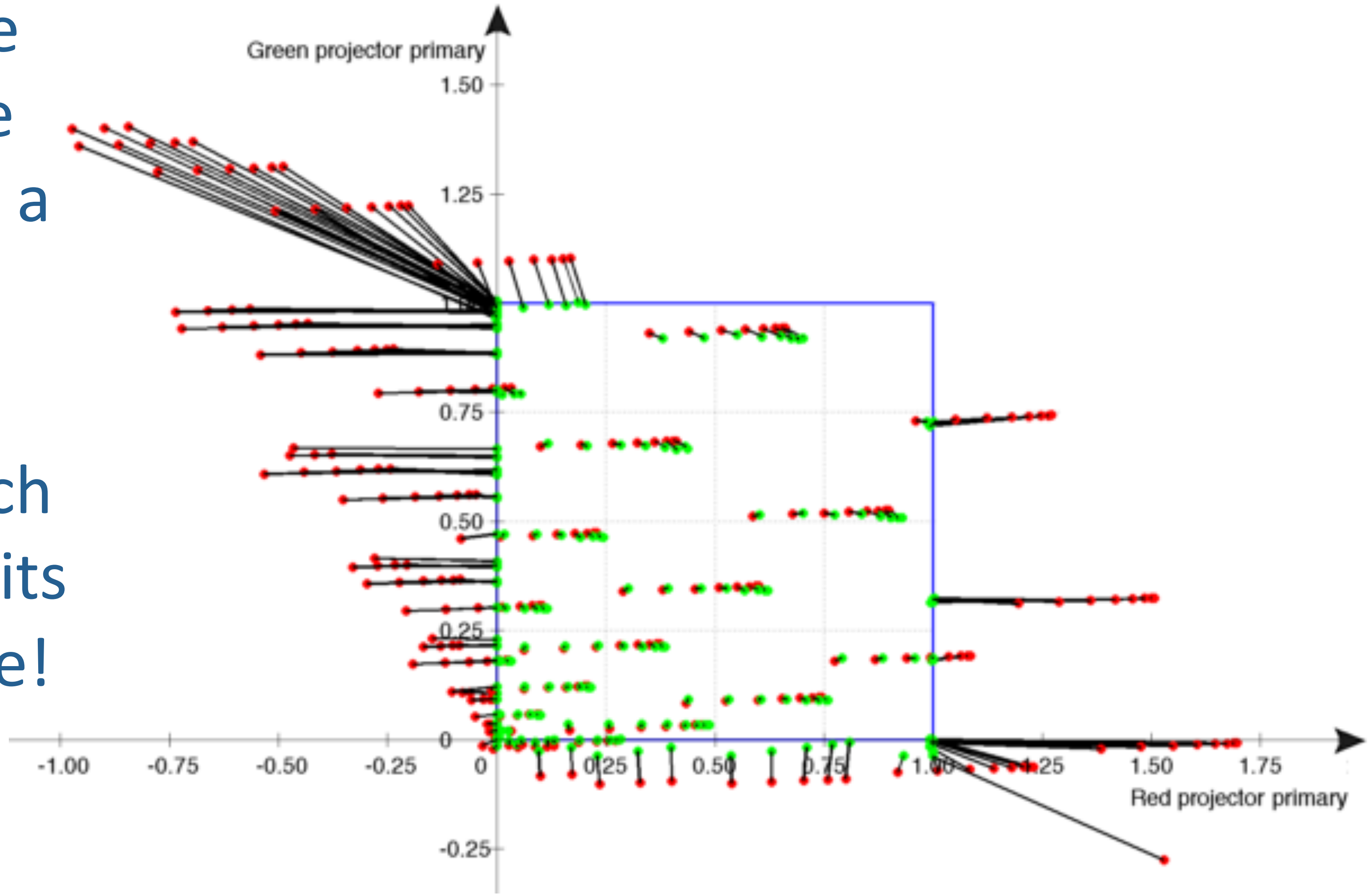
- Mapping in XYZ:



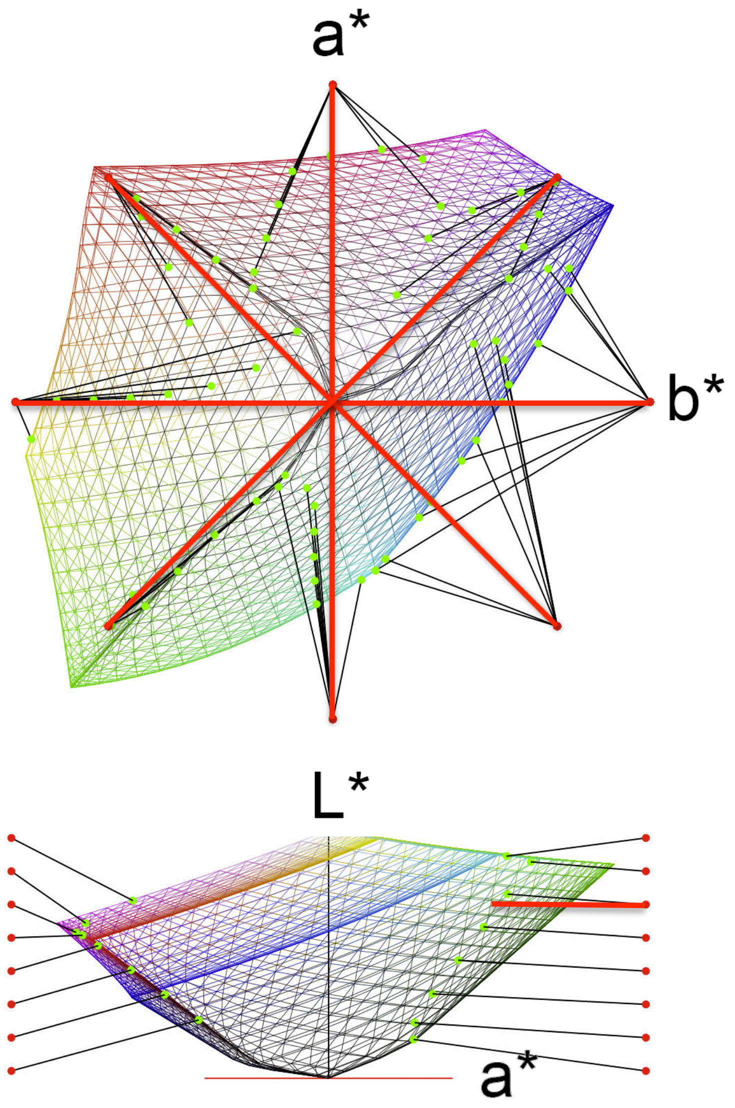
Current projector's gamut mapping

Mapping with the projector's native primary colors as a basis.

→ It just clips each R,G,B-channel in its native color space!

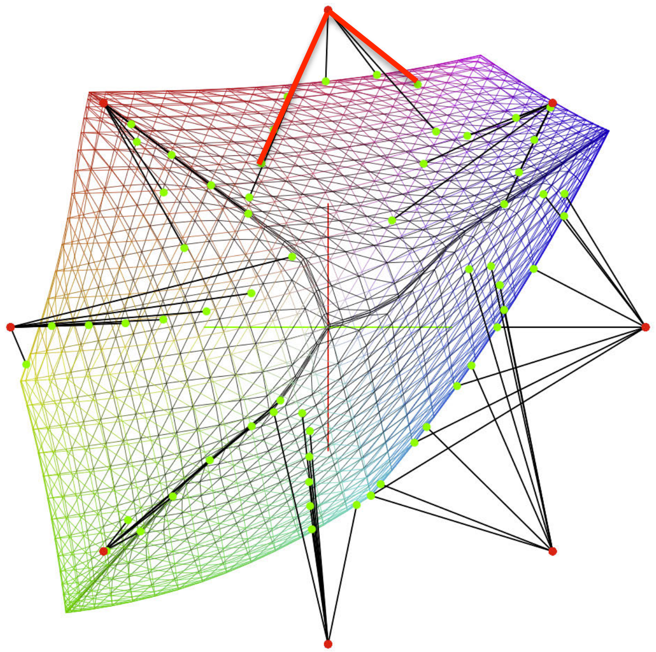


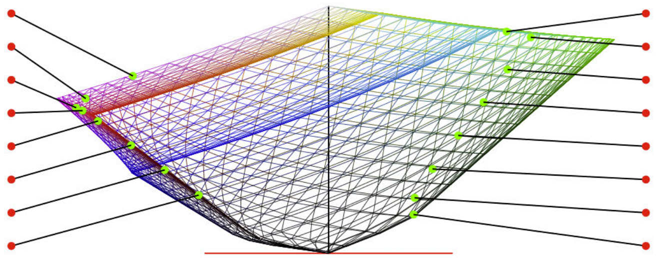
Gamut mapping algorithms: Introduction



Gamut mapping algorithms: PCLIP

3.1 PCLIP

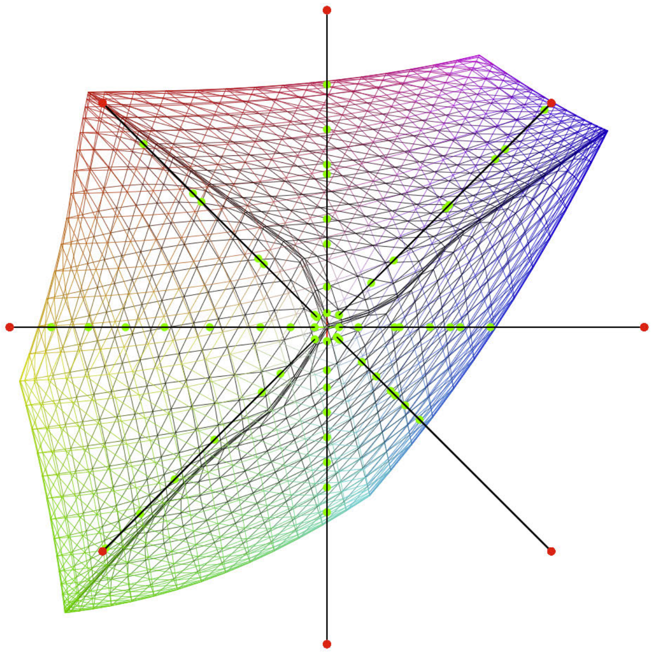


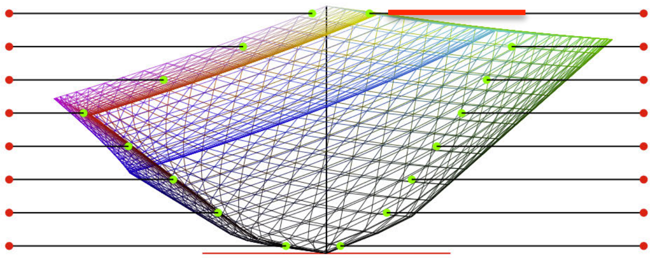


Gamut mapping algorithms: Introduction

Gamut mapping algorithms: LCLIP

3.2 LCLIP

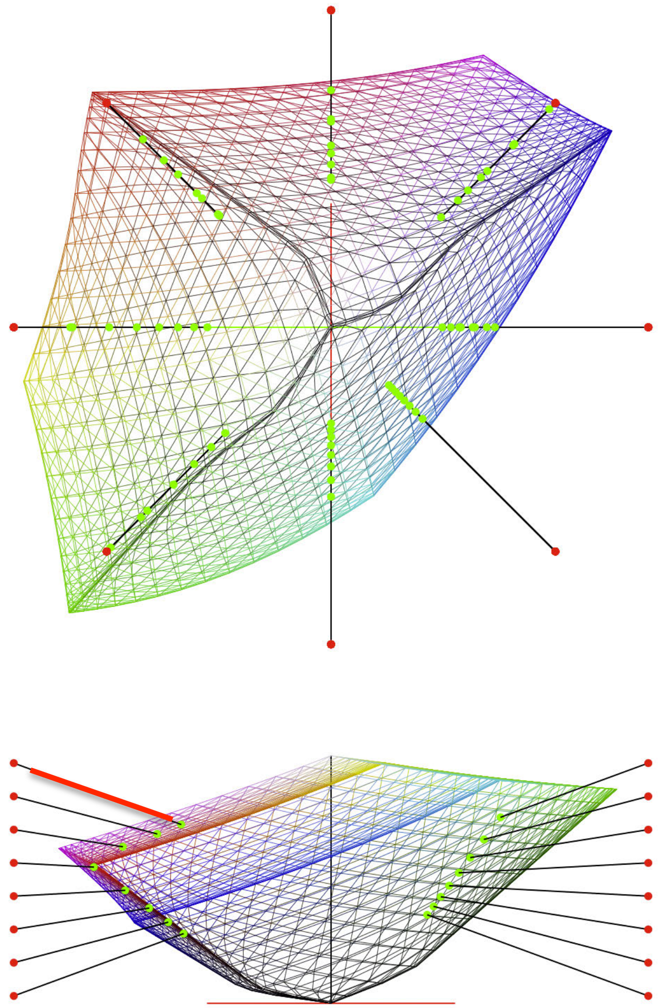




Gamut mapping algorithms: Introduction

Gamut mapping algorithms: SCLIP

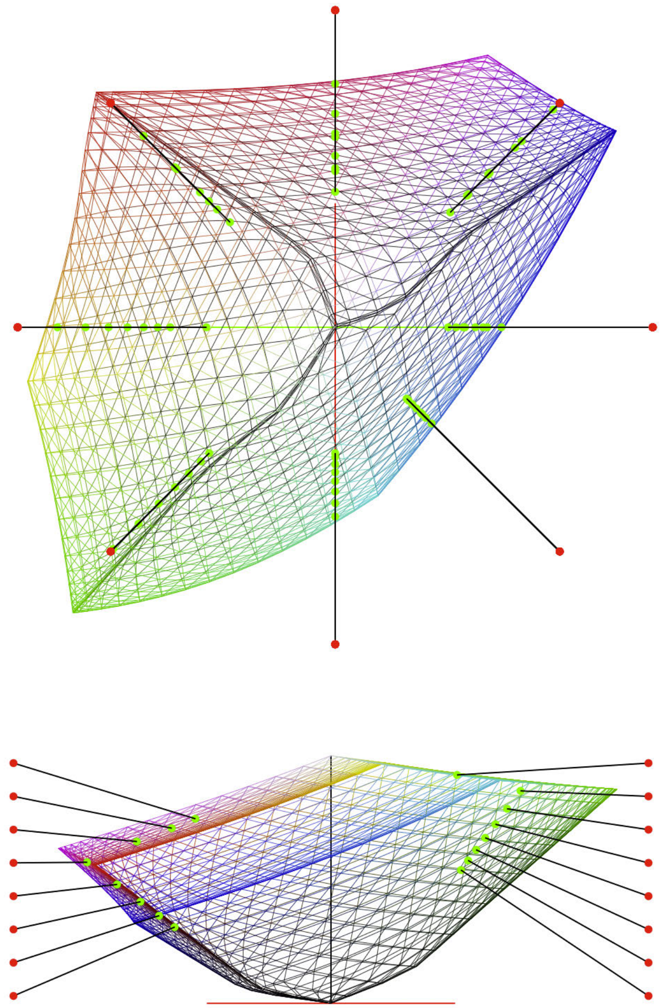
3.3 SCLIP



Gamut mapping algorithms: Introduction

Gamut mapping algorithms: CCLIP

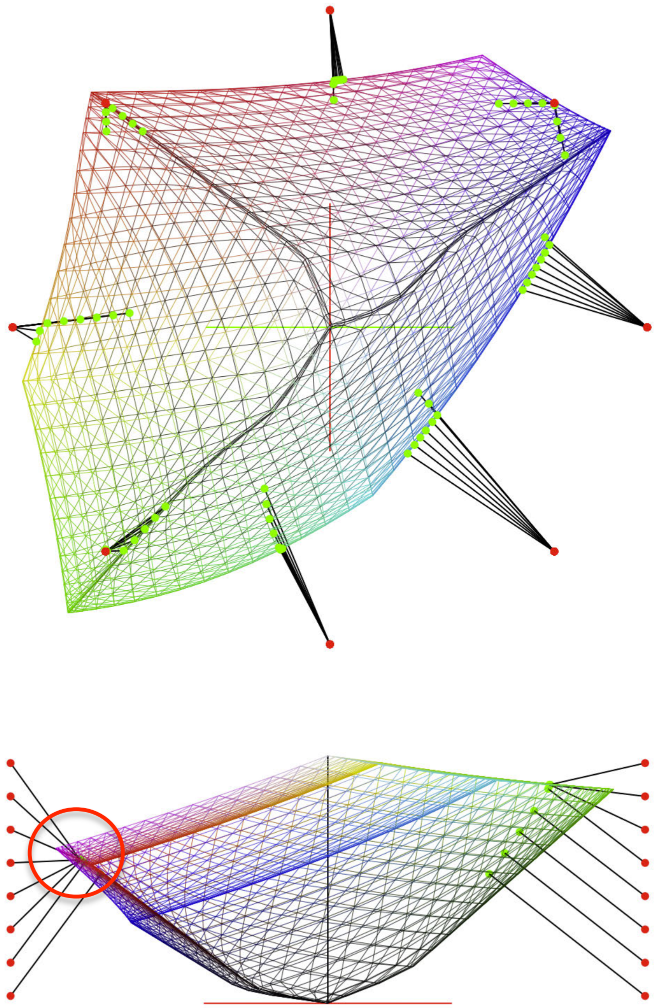
3.4 CCLIP



Gamut mapping algorithms: Introduction

Gamut mapping algorithms: mindE

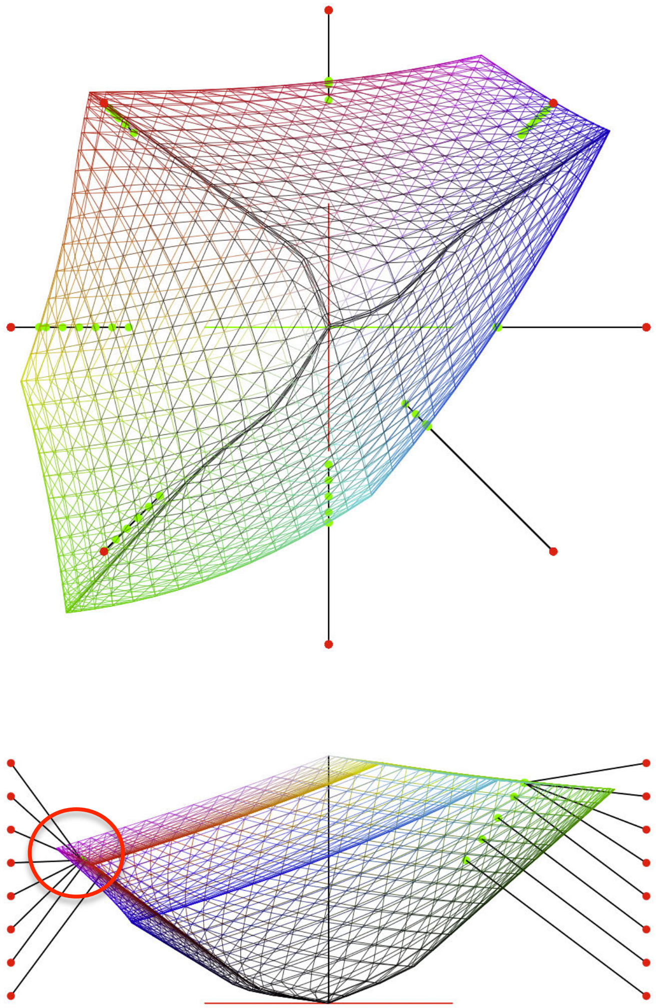
3.5 mindE



Gamut mapping algorithms: Introduction

Gamut mapping algorithms: HPmindE

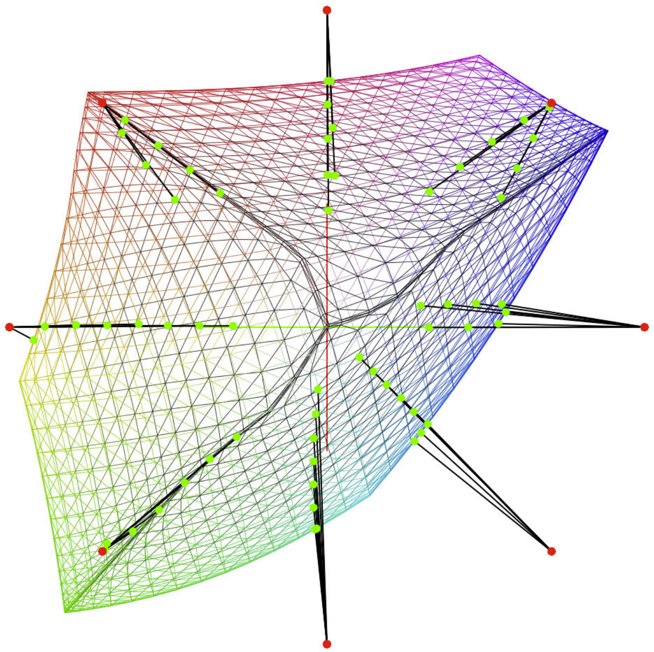
3.6 HPmindE

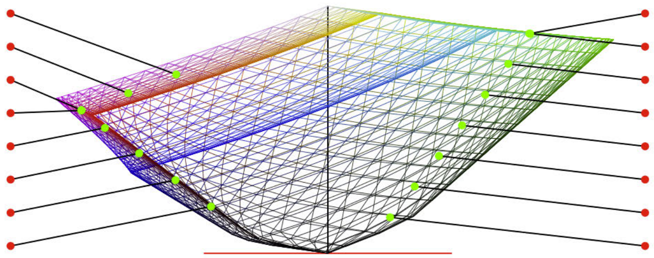


Gamut mapping algorithms: Introduction

Gamut mapping algorithms: WmindE

3.7 WmindE





Color spaces for gamut mapping

Color spaces / color appearance models evaluated:

- CIE 1976 L*a*b*
- CIECAM02-HPE
- Fritz Ebner's IPT

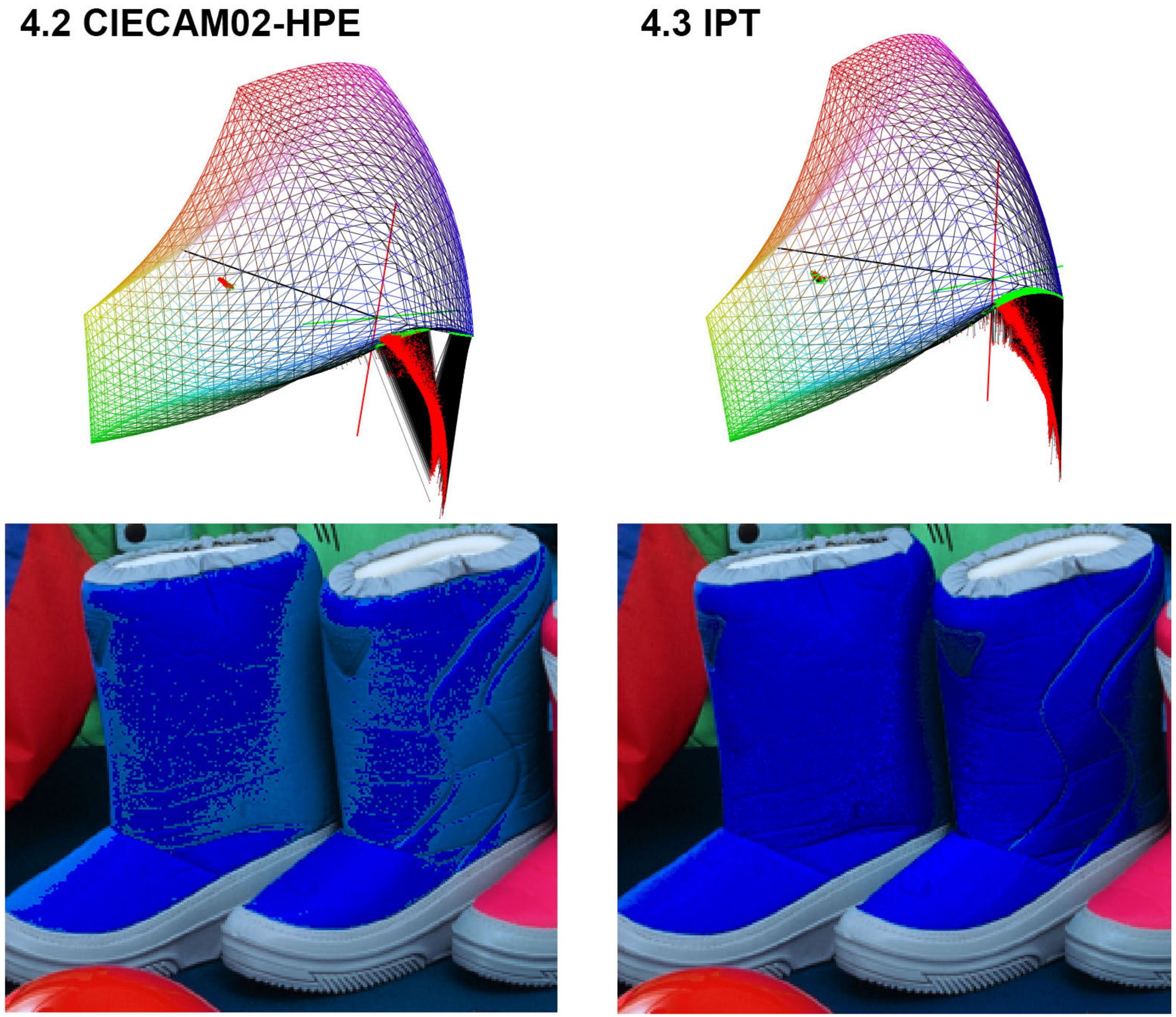
Color spaces for gamut mapping

- L*a*b* is not hue-linear enough:

Color spaces for gamut mapping

Artifacts due to concave gamut boundary:

- All mindE Algorithms affected.
- In our test set IPT performed more robust than CIECAM02-HPE.
- More test images needed.



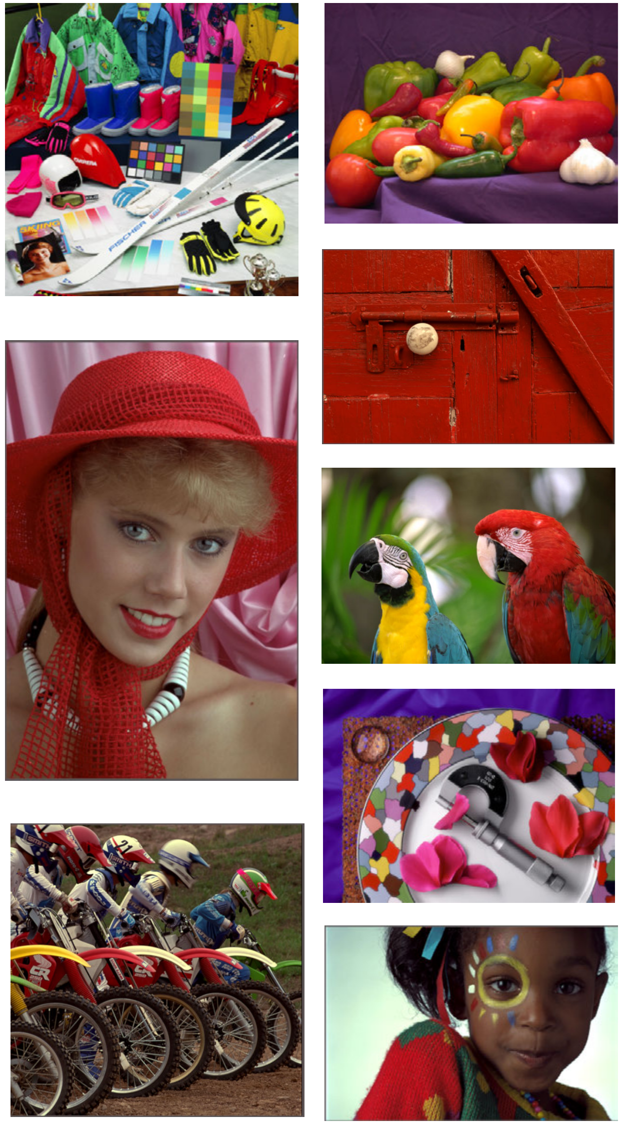
User Study

16 Participants:

- 9 Expert, 7 Non-Expert.

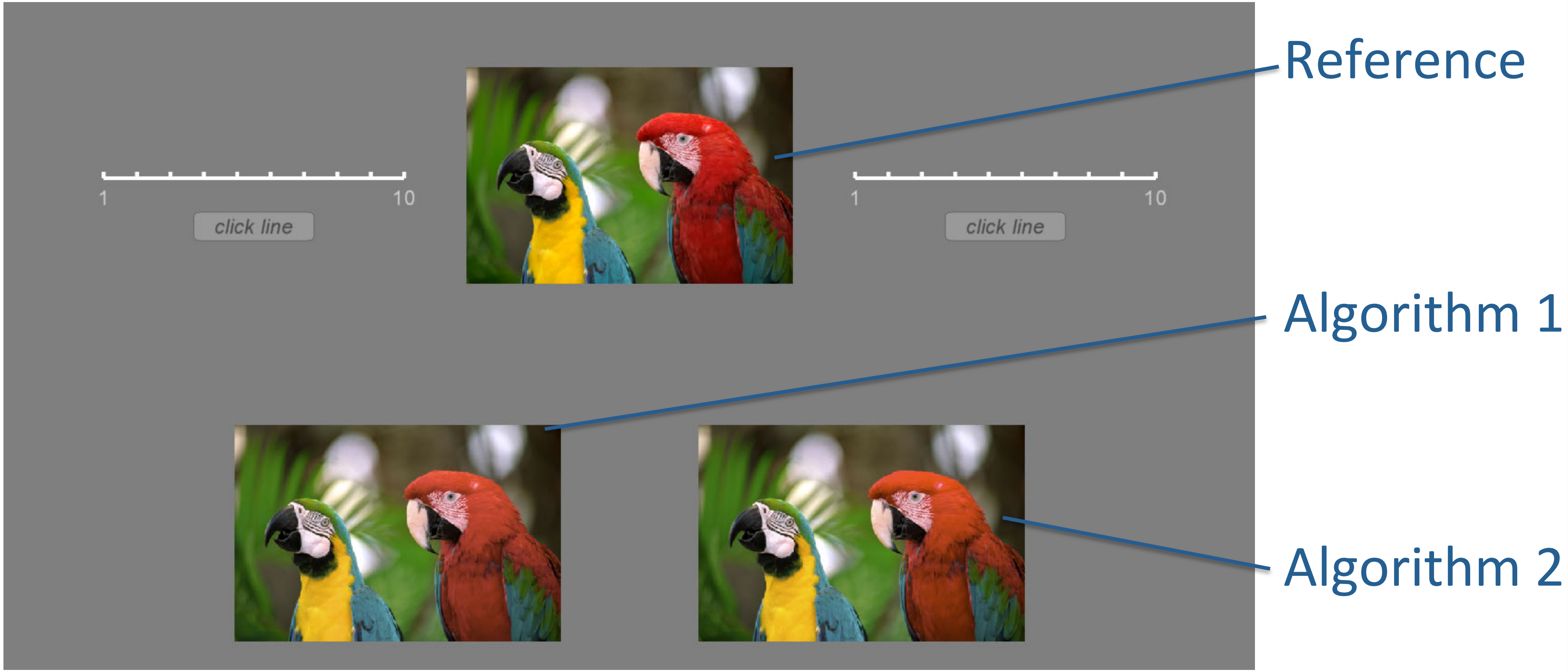
10 Images:

- Graded on modified DLP-Cinema™ projector to make use of P3laser gamut.
- Mapped via PCLIP, SCLIP and WmindE in IPT.
- Pairwise comparison PCLIP vs. SCLIP and PCLIP vs. WmindE.



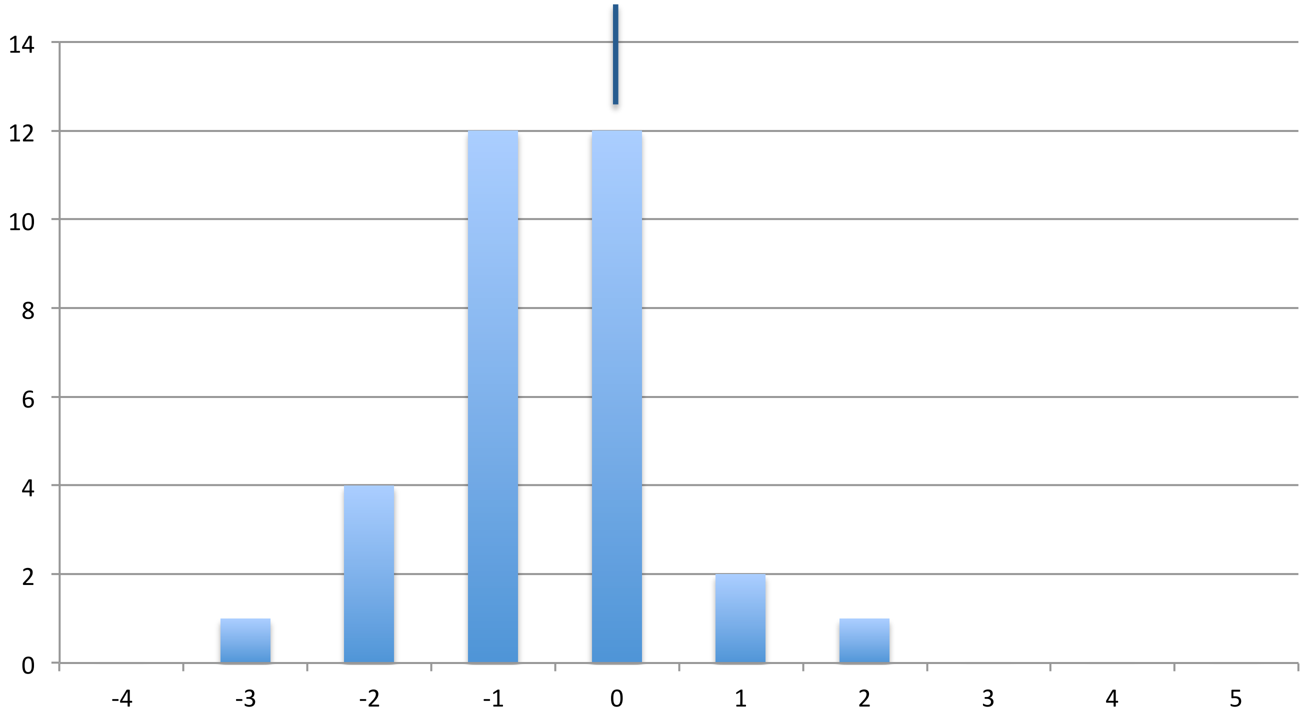
User Study

Design: Pairwise comparison



Loss of Detail

Relative perceived difference:

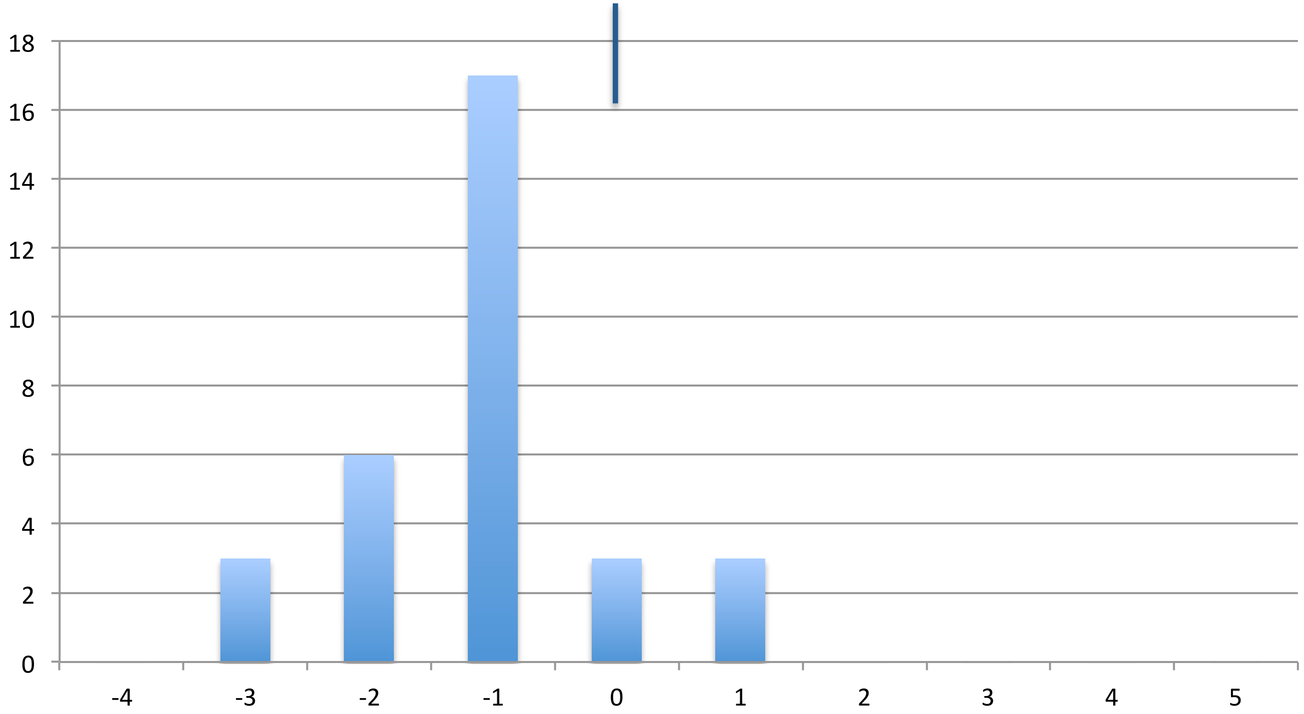


WmindE PCLIP

User Study

Change of hue

Relative perceived difference:

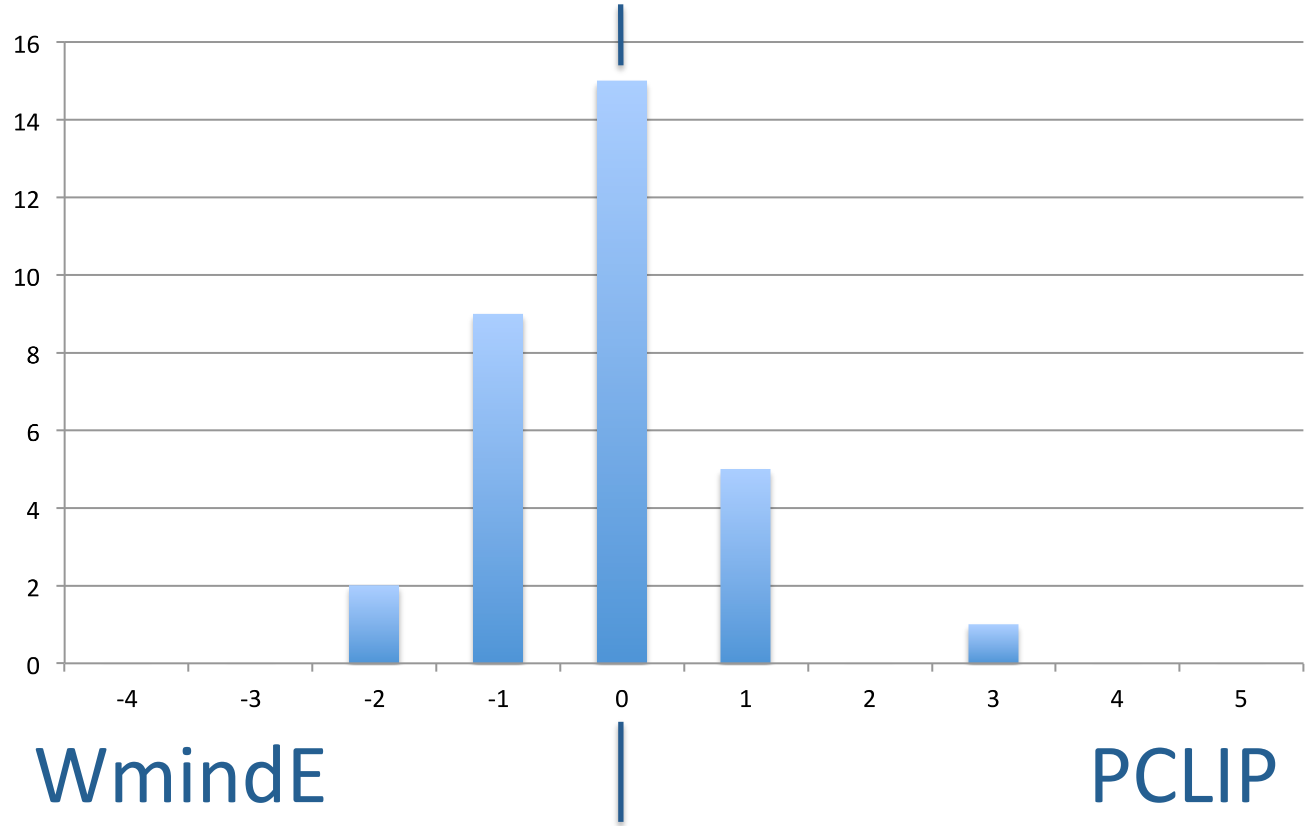


WmindE | PCLIP

Study

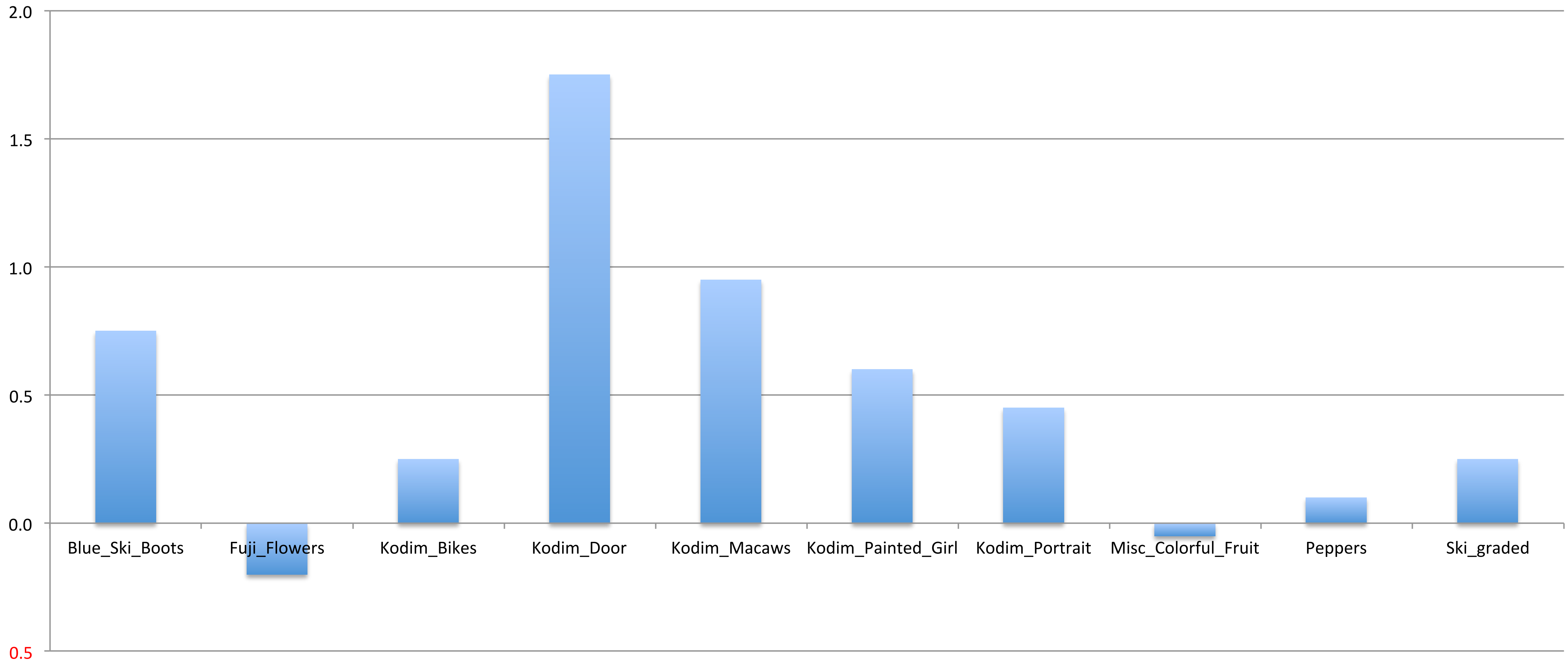
Changes in smaller areas were not found to be significant:

Relative perceived difference:



User Study

- Mean preference of WmindE over PCLIP:



Results of the User Study

- Differences in gamut mapping from laser projection to XENON-projection (DCI-P3ref) are perceived by average users.
- Expert and non expert users don't differ significantly.
- 80% of the users favor WmindE over PCLIP.

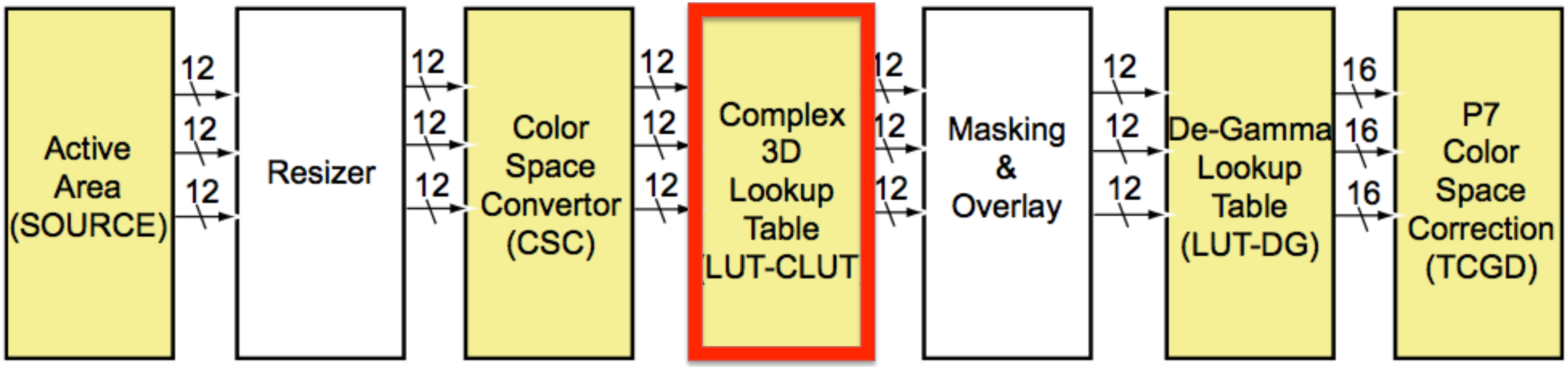
Implementation

All Algorithms except PCLIP to complex to render in realtime

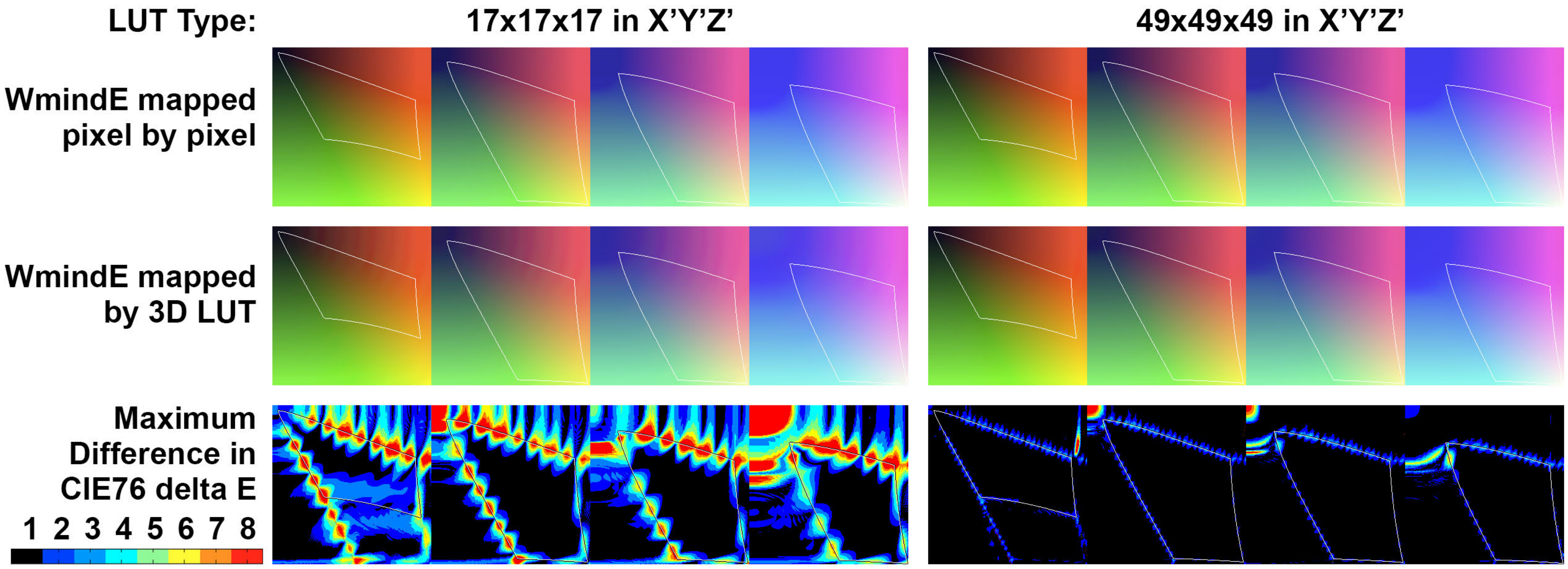
→ Put a 3D LUT in the processing chain of the projector

Maximum 3D LUT size:

- Series 1: 49x49x49
- Series 2: 17x17x17



Implementation



Only series 1 projectors can be retrofitted using a simple X'Y'Z' to X'Y'Z' LUT

Results

- We investigated current gamut mapping algorithms and color spaces suitable for gamut mapping for digital cinema.
- WmindE in IPT offers better detail preservation than the current algorithm PCLIP while retaining chroma.
- WmindE was preferred over PCLIP by 80% of the users.
- Series 1 projectors can easily be retrofitted using a 3D-LUT

Call to action

- Final evaluation can only be done by the whole industry because results of gamut mapping heavily depend on the selected images and subjective preference.
- Download LUTs and reference images from: www.hdm-stuttgart.de/~froehlichj
- Discuss standardization of gamut mapping for digital cinema!

Acknowledgements

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Backup Slide: Automatic gamut mapping?

Is it reasonable to use automatic gamut mapping in cinema, compared to the manual creation of TV-deliveries?

- Viewing conditions: *dark vs. dim.*
- Medium: *reflecting screen vs. self luminous monitor.*
- Visual expectations: *cinema vs. TV.*
- Change of contrast range: ~1500:1 → ~100:1